

Polarization of AGN Jets

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Abstract. The sensitivity, stability, and uniformity of calibration of the VLBA has revolutionized parsec-scale polarization studies of AGN jets. Not only does polarization probe the magnetic field structures of jets, serving as a hydrodynamic tracer of shocks, bends, and shear, but polarization also probes the medium through which it propagates by encoding the signature of Faraday effects along the line of sight. I review advances made by the VLBA in studying the polarization of jets to probe their magnetic field structures, properties of the jet plasma, and properties of the external environment. This review covers both linear and circular polarization and is set in the context of outstanding questions in the field.

1. Introduction

The Very Long Baseline Array¹ (VLBA) has revolutionized the study of parsec-scale polarization from jets of active galactic nuclei (AGN) by allowing highly sensitive, multi-frequency, multi-epoch polarization studies for a large number of sources. In recent years, we have begun to use these capabilities to address a number of fundamental open questions regarding the structure, composition, environment and evolution of AGN jets.

Perhaps the most glaring (and difficult) of these open questions, is that after forty years of study, we still do not know whether AGN flows are primarily an electron-proton (e^-p^+) plasma or a electron-positron (e^-e^+) plasma. Another fundamental issue is that while the synchrotron radiation we observe is produced by a power-law particle energy spectrum, we do not know where (or how) that spectrum cuts off at low energy. These low energy particles are particularly important as they dominate the bulk kinetic energy of the jet (e.g. Celotti & Fabian 1993). On the fundamental question of jet structure, the full three dimensional magnetic field configuration of jets is still only vaguely understood. We know that jets contain a significant (and perhaps dominant) component of disordered magnetic fields which are shocked or sheared hydro-dynamically, but we do not know if the jets have an over-arching field structure (with helical, toroidal and/or poloidal components) which is related to the black-hole/accretion disk system.

¹The VLBA is an instrument of the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

2. 3-D Magnetic Field Structures of Jets

In the absence of Faraday rotation, linear polarization gives a measure of the net field order along the line of sight, projected onto the plane of the sky; however, interpretation of polarization patterns in jets is complicated by the fact that a variety of three-dimensional magnetic field models can produce very similar two dimensional polarization structures. One example is a helical magnetic field which will produce linear polarization that is either parallel (Stokes $-Q$) or transverse (Stokes $+Q$) to the jet due to cancellation of the Stokes U component from the back to the front of the jet. A toroidal field will also produce parallel polarization, and if viewed from an angle may have transverse polarization at the edges of the jet. Parallel or transverse polarization (as well as oblique polarization angles) can also be produced hydro-dynamically by shocking or shearing of magnetic fields.

Disentangling these effects is a difficult problem, and a first step is to catalog the types of polarization (fractional amounts and orientations) seen in jets. A great deal of work has been done to catalog and compare the parsec scale linear polarizations for a large number of AGN jets at a variety of wavelengths (e.g. Cawthorne et al. 1993, Gabuzda et al. 2000, Lister & Smith 2000, Lister 2001, Marscher et al. 2002, Pollack et al. 2003). Typical AGN cores are weakly polarized at the few percent level with higher polarization being revealed at higher frequencies, and jet features typically have 5 – 10% polarization with a tail up to a few tens of percent. A number of conflicting reports have been published regarding the relative orientation of jet polarization to jet direction at $\lambda 6$ cm (Cawthorne et al. 1993; Gabuzda et al. 2000; Pollack et al. 2003); averaging over these results it seems that there is no relation for quasars, but BL Lac objects do tend to have an excess of parallel polarization with a peak near $|\theta - \chi| = 0$ degrees. Higher frequency results ($\lambda\lambda$ 1.3 & 0.7 cm), which are less subject to contamination by Faraday rotation, show an excess near 0 degrees with a broad tail for both kinds of objects (Lister & Smith 2000, Lister 2001, & Marscher et al. 2002). Marscher et al. (2002) have noted that this distribution is consistent with oblique shocks.

Most parsec scale polarization observations to date are sensitive only to polarization in the brightest regions of jet emission. These regions are enhanced, most likely due to shocks or bends in the jet, and therefore the measured polarizations may not accurately reflect the full jet magnetic field structure. A excellent example is the source 1055+018 (Attridge et al. 1999) which with four hours of VLBA+Y1 time at $\lambda 6$ cm reveals a remarkable sheath-like polarization structure around the main jet. This structure was not visible in two previous one hour VLBA observations also at $\lambda 6$ cm (Attridge 1999). It is very important to study more sources with highly sensitive polarization observations to see if we are missing important pieces of the jet magnetic field structure.

Recent work by Asada (2002) and Gabuzda (2003, this volume) has suggested that jets may contain a significant toroidal component of magnetic field that is visible in the form of transverse Faraday rotation measure gradients. Gradients in rotation measure can also form if there is a non-uniform distribution in the external parsec-scale Faraday screen, so more work is necessary to be sure of this interpretation. However, the results are tantalizing, and important three dimensional magnetic field information can be gleaned from Faraday rotation

if it can be shown that this rotation is occurring internal to the jet. Likewise, circular polarization can also yield constraints on the three dimensional field structure.

2.1. A Probe of Jet Hydrodynamics: Polarization Evolution

Observing the time evolution of jet magnetic fields is important for understanding the magneto-hydrodynamics of jets. The VLBA has made it possible to conduct rapid monitoring campaigns of parsec scale jet structure. For example, time sequences of 3C 120 made by Gomez et al. (2000) at λ 1.3 cm, reveal a wealth of detailed variation in the observed polarization including a possible jet-cloud interaction. Interpreting these results in detail is extremely difficult and probably requires a new generation of hydrodynamic jet models which include magneto-hydrodynamics and full Stokes polarization propagation. Such models are on the way (see Gomez, J. 2003, this volume) and their first test will be to see if they can reproduce the average polarization behavior of jet components followed in recent monitoring programs.

In Homan et al. (2002) we analyzed observations of twelve AGN jets from a six epoch, dual-wavelength (λ 2 & 1.3 cm) VLBA experiment to find year-long trends in polarization behavior of jet components over time and the fluctuations about those trends. Within our small sample, we found jet components tended to increase in fractional polarization as they moved down the jet. We also found there was a tendency for the polarization angles of jet components to rotate in the direction of being transverse to the jet. We argued that these two pieces of information suggested growing longitudinal field order in the jet. We also observed fluctuations in polarization position angles about the longer term trends, these fluctuations tended to be larger for more weakly polarized jet features as might be expected if the changes reflect internal changes in their magnetic field structure. With the possible exception of 3C 273, the polarization changes we observed could not be easily explained by Faraday rotation (or depolarization) and appeared to reflect real changes in the magnetic structure of jet features over time.

3. Faraday Rotation

Faraday rotation is the rotation of the plane of linear polarization during propagation of a radio wave through a magnetized plasma and is proportional to the square of the wavelength. The Faraday rotation we observe is the net effect along our line of sight: through our galaxy, across intergalactic space, through the host galaxy of the quasar, and even through the jet itself. However, it appears that Faraday rotation at centimeter wavelengths is dominated by screens external but near to the radio jet, probably in the narrow line region of the AGN (Taylor 1998, 2000).

Quasars typically have rotation measures of 1000 up to a few thousand radians/m² in their core regions and on the order of 100 rad/m² in their jets (Taylor 1998, 2000; Zavala & Taylor 2003). BL Lac objects are similar to quasars with perhaps a bit lower values in the core (Gabuzda et al. 2001, 2003; Zavala & Taylor 2003). Galaxies have stronger Faraday screens than either quasars or BL Lacs and often have depolarized cores (Taylor et al. 2001; Zavala & Taylor

2002). Exceptions to the above rules do exist, the CSS quasar OQ172 was found to have $40,000 \text{ rad/m}^2$ in its core (Udomprasert et al. 1997), and Attridge et al. (2003, this volume) have used 86 GHz VLBA results to show that a rotation measure gradient of $\sim 30,000 \text{ rad/m}^2$ must exist between two jet components in 3C 273. The existence of such a high rotation measure gradient in 3C 273, suggests the need for further high frequency, high resolution Faraday rotation measure studies of AGN cores.

Are we actually seeing narrow line clouds in these kinds of observations? With only a $\sim 1\%$ estimated covering factor for a uniform cloud distribution, Zavala & Taylor (2002) suggest that clouds may be entrained by the jet, perhaps in a boundary layer. There is some direct evidence for jet-cloud interactions with large rotation measures observed in bends of 3C 120 (Gomez et al. 2000), 0820+225 (Gabuzda et al. 2001), and 0548+165 (Mantovani et al. 2002).

If the Faraday rotation does occur in a boundary layer, the magnetic fields responsible for the rotation may be directly related to the magnetic field structure of the jet. Additionally, there may be significant Faraday rotation internal to the jet in some cases. We argued this was the case for 3C 279 to explain our circular polarization observations (Wardle et al. 1998), and Cotton et al. (2003) have seen what appears to be internal Faraday rotation in 3C 454. In addition to giving us information about the field structure of the jet, internal Faraday rotation is highly sensitive to the low energy end of the particle energy spectrum and combined with circular polarization observations may allow us to constrain that population.

4. Circular Polarization

Low resolution measurements made during the 1970s and early 1980s found circular polarization to be only a tiny fraction (0.1% was considered strongly polarized) of the integrated synchrotron emission from AGN jets (Weiler & de Pater 1983, and sources therein). In 1988, Jones published computer simulations of the radiative transfer in jets showing that local levels of circular polarization could exceed 0.5%, and he suggested that high resolution (VLBI) circular polarization observations could provide important constraints on jet physics. Indeed we have found local levels of circular polarization exceeding 0.5% in a handful of sources, including 3C 84, PKS 0528+134, PKS 0607-157, 3C 273, and 3C 279 (Wardle et al. 1998; Homan & Wardle 1999, 2003). Such strongly polarized sources are the exception, in general we find that only 5 – 10% of sources have local circular polarization of 0.3% or higher (Homan et al. 2001; pre-liminary results from the MOJAVE program, see Lister, M. 2003, this volume). When we do detect circular polarization, it is almost always associated with the VLBI core, although 3C 84 is a clear exception with well resolved structure in circular polarization (Homan & Wardle 1999, and ApJ submitted).

A potentially powerful diagnostic of circular polarization is the relationship between circular and linear polarization. In general, linear polarization levels exceed those for circular, but there was no other clear relationship for a sample of 40 sources we studied at λ 6 cm (Homan et al. 2001). This work needs to be repeated at shorter wavelengths to eliminate possible contamination by Faraday depolarization of the linear. Interestingly, low luminosity AGN seem to be an

exception to the above rule with circular polarization exceeding linear in Sgr A* (Bower et al. 1999), M81* (Brunthaler et al. 2001), and M87 (recent MOJAVE result, unpublished data). In our original study (Homan & Wardle 1999), the two lowest luminosity objects in which we detected circular polarization, 3C 84 and 3C 273, also had as much or more circular polarization than linear. This relation between luminosity and the linear to circular polarization ratio needs to be investigated further; however, it may simply be due to the close proximity of the low luminosity objects which gives better linear resolution. In those nearby objects, what we are seeing as the core is embedded in a higher density environment which could lead to external depolarization of the linear polarization.

A key open question in the study of circular polarization is the generation mechanism. Circular polarization in AGN jets may be produced either as a direct (intrinsic) component of synchrotron radiation or through the Faraday conversion process which converts linear to circular polarization. Intrinsic circular polarization requires a significant charge imbalance in the radiating particles (an e^-p^+ jet) and strong uni-directional magnetic fields in the jet. This combination is precisely the combination that will lead to very large amounts of internal Faraday rotation unless the cutoff in the relativistic particle energy spectrum is rather high, $\gamma_i \gtrsim 100$ (Wardle 1977). Faraday conversion on the other hand, requires a large number of low energy relativistic particles in the jet to do the conversion and hence a relatively low cutoff in the particle energy spectrum, $\gamma_i \lesssim 20$ (Wardle et al. 1998). A low cutoff in the particle energy spectrum may imply a jet dominated by e^-e^+ pairs on kinetic luminosity grounds (e.g. Celotti & Fabian 1993), and we argued this is the case for 3C 279 (Wardle et al. 1998), but these are difficult arguments to make conclusively. Theoretically (e.g. Jones 1988) it appears easier to generate large amounts of circular polarization through the Faraday conversion process, but direct observational evidence favoring one mechanism over the other remains scarce (e.g. Homan & Wardle 2003).

Another important open question is the sign consistency of circular polarization in individual AGN. A consistent sign of circular polarization would indicate a consistent underlying magnetic field structure, such as the poloidal field direction or the twist of a helical field. Komessaroff et al. (1984) found a tendency for objects in their sample to show the same sign of circular polarization over their three to five year observing window. We found the same to be true over a one year period for sources undergoing strong core outbursts (Homan & Wardle 1999). In Homan et al. (2001), we compared recent circular polarization results to those from ~ 20 years ago, and found in five of six cases the same sign of circular polarization today as in the earlier measurements. On the basis of these small statistics, we speculated that long-term consistency in the sign of circular polarization may be a general property of AGN, with the sign set by the super massive black hole/accretion disk system.

Bower et al. (2002) have shown convincingly that Sgr A* has indeed maintained the same sign of circular polarization over the last 20 years. Our time baseline for VLBA results is also growing. Combining results from a number of programs (Homan & Wardle 1999; Homan, unpublished data; M. Lister, private communication; pre-liminary MOJAVE results), there is now nearly seven years

of VLBA data on the superluminal quasars 3C 273 and 3C 279 at 15 or 22 GHz. The sign of circular polarization in those objects has remained the same over that period and the signs observed today match those measured ~ 20 years ago at lower frequency (Weiler & de Pater 1983). Despite this progress, we still need better observational evidence that sources in general have a preferred sign of circular polarization and to find on what timescale any preferred sign may persist. Indeed, the fact that there is clear evidence for changes in sign in some cases (e.g. Aller et al. 2003) indicates that more monitoring is needed to determine if sign changes of this type represent fundamental changes in overall jet magnetic field structure or stochastic changes in the tangled component of magnetic field.

5. The Future

The future looks bright for parsec scale polarization studies of AGN jets. A number of fundamental questions regarding the physics of jets and their environment remain open, and polarization can provide useful insights to many of them. Over the next few years, observers will continue to exploit the unique capabilities of the VLBA to study polarization. In studying the three-dimensional magnetic field structures of jets, Faraday corrected polarization maps will be important to remove the Faraday rotation which plagues images made at lower frequency. Longer integrations and greater sensitivity will also play a key role by uncovering the full polarization structure of the jet, as in the case of 1055+018. Faraday rotation studies and circular polarization observations may give important additional information about the three-dimensional structure of jet magnetic fields. And following the time evolution of polarization will continue to give us a better handle on the magneto-hydrodynamics of jets.

In the study of Faraday screens surrounding jets, higher frequency observations will measure and resolve the large Faraday depths surrounding VLBI cores. Studies of the rotation measure distribution transverse to jets will also be important for evaluating models of toroidal/helical field structures. Jet-cloud interactions seen through the effects of Faraday rotation are particularly intriguing for what they might reveal about both jets and clouds. Clear evidence for internal Faraday rotation would also be very important as it would help to constrain the low energy end of the particle distribution in jets.

Studies of circular polarization need longer time baselines to better evaluate the issue of sign consistency in individual sources. Better spectral studies of circular polarization are also crucially important to constrain the emission mechanism; such studies will require enhanced sensitivity and improved calibration techniques so that several frequencies can be observed quasi-simultaneously. Higher resolution studies will also be very useful to alleviate confusion due to the inhomogeneous VLBI core and to resolve the region where circular polarization is actually generated.

References

- Aller, H. D., Aller, M. F., & Plotkin, R. 2003, In: *Circular Polarization of Relativistic Jet Sources* eds. R.P. Fender & J.-P. Macquart, Ap&SS, in press.
- Asada, K. et al. 2002, PASJ, 54, L39
- Attridge, J. M. 1999, ApJ, 518, L87
- Attridge, J. M. 1999, Ph.D. Thesis
- Bower, G. C., Falcke, H., & Backer, D. C. 1999, ApJ, 523, L29
- Bower, G. C. et al. 2002, ApJ, 571, 843
- Brunthaler, A. et al. 2001, ApJ, 560, L123
- Cawthorne, T. V. et al. 1993, ApJ, 416, 519
- Celotti, A. & Fabian, A. C. 1993, MNRAS, 264, 228
- Cotton, W. D. et al. 2003, A&A, 403, 537
- Gabuzda, D. C. & Chernetskii, V. A. 2003, MNRAS, 339, 669
- Gabuzda, D. C., Pushkarev, A. B., & Cawthorne, T. V. 2000, MNRAS, 319, 1109
- Gabuzda, D. C., Pushkarev, A. B., & Garnich, N. N. 2001, MNRAS, 327, 1
- Gomez, J.-L. et al. 2000, Science, 289, 2317
- Homan, D. C. et al. 2002, ApJ, 568, 99
- Homan, D. C., Attridge, J. M., & Wardle, J. F. C. 2001, ApJ, 556, 113
- Homan, D. C. & Wardle, J. F. C. 1999, AJ, 118, 1942
- Homan, D. C. & Wardle, J. F. C. 2003, In: *Circular Polarization of Relativistic Jet Sources* eds. R.P. Fender & J.-P. Macquart, Ap&SS, in press, astro-ph/0211183
- Jones, T. W. 1988, ApJ, 332, 678
- Komesaroff, M. M. et al. 1984, MNRAS, 208, 409
- Lister, M. L. 2001, ApJ, 562, 208
- Lister, M. L. & Smith, P. S. 2000, ApJ, 541, 66
- Mantovani, F. et al. 2002, A&A, 389, 58
- Marscher, A. P. et al. 2002, ApJ, 577, 85
- Pollack, L. K., Taylor, G. B., & Zavala, R. T. 2003, ApJ, 589, 733
- Taylor, G. B. 1998, ApJ, 506, 637
- Taylor, G. B. 2000, ApJ, 533, 95
- Taylor, G. B., Hough, D. H., & Venturi, T. 2001, ApJ, 559, 703
- Udomprasert, P. S. et al. 1997, ApJ, 483, L9
- Wardle, J. F. C. et al. 1998 Nature, 395, 457
- Wardle, J. F. C. 1977, Nature, 269, 563
- Weiler, K. W. & de Pater, I. 1983, ApJS, 52, 293
- Zavala, R. T. & Taylor, G. B. 2002, ApJ, 566, L9
- Zavala, R. T. & Taylor, G. B. 2003, ApJ, 589, 126